

Optical flares and flaring oscillations on the M-type eclipsing binary CU Cnc

Qian S.-B.^{1,2,3}, Zhang J.^{1,2,3}, Zhu L.-Y.^{1,2}, Liu L.^{1,2}, Liao W.-P.^{1,2}, Zhao E.-G.^{1,2}, He J.-J.^{1,2}, Li L.-J.^{1,2,3}, Li K.^{1,2,3} and Dai Z.-B.^{1,2}

ABSTRACT

We report here the discovery of an optical flare observed in R band from the red-dwarf eclipsing binary CU Cnc whose component stars are at the upper boundary of full convection ($M_1 = 0.43$ and $M_2 = 0.4 M_\odot$, M_\odot is the solar mass). The amplitude of the flare is the largest among those detected in R band (~ 0.52 mag) and the duration time is about 73 minutes. As those observed on the Sun, quasi-periodic oscillations were seen during and after the flare. Three more R-band flares were found by follow up monitoring. In total, this binary was monitored photometrically by using R filter for 79.9 hours, which reveals a R-band flare rate about 0.05 flares per hour. These detections together with other strong chromospheric and coronal activities, i.e., very strong H_α and H_β emission features and an EUV and X-ray source, indicate that it has very strong magnetic activity. Therefore, the apparent faintness (~ 1.4 magnitude in V) of CU Cnc compared with other single red dwarfs of the same mass can be plausibly explained by the high coverage of the dark spots.

Subject headings: Stars: binaries : close – Stars: binaries : eclipsing – Stars: individuals (CU Cnc) – Stars: activity – Stars: flare – Stars: late-type

1. Introduction

Though M-type stars (red dwarfs with mass less than $0.6 M_\odot$, and M_\odot is the solar mass) are the most populous stellar objects in the Galaxy, to date, only about a dozen of eclipsing

¹National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, P.O. Box 110, 650011 Kunming, P. R. China (qsb@ynao.ac.cn)

²Key laboratory of the structure and evolution of celestial objects, Chinese Academy of Sciences, P.O. Box 110, 650011 Kunming, P. R. China

³Graduate University of the Chinese Academy of Sciences, 100049 Beijing, P. R. China Yuquan Road 19#, Sijingshang Block, 100049 Beijing City, P. R. China

red-dwarf binaries in detached systems was detected and studied in details because of the low probability of finding them and their very low intrinsic brightness (e.g., Blake et al. 2008; Irwin et al. 2009; Torres & Ribas 2002; Morales et al. 2009). Fundamental stellar properties of these binaries, especially masses and radii, can be measured in a high precision (better than 2%). Therefore, they play a key role in our understanding of stellar physics near the bottom of main sequence in the Hertzsprung-Russell diagram.

With an orbital period of 2.771468 days, CU Cancri (=GJ 2069A, HIP 41824) is one of a few extremely low-mass eclipsing binaries (e.g., Ribas, 2003; Blake et al., 2008; Irwin et al., 2009; Morales et al., 2009). It is a nearby ($d=12.8$ PC) 11.9-mag spectroscopic binary system with M3.5 Ve components, where the "e" refers to the Balmer lines being in emission in the "quiescent" state (e.g., Reid et al., 1995; Delfosse et al., 1999b). Photometric monitoring with the 0.7-m Swiss telescope at the European Southern Observatory revealed that it is an eclipsing binary (Delfosse et al. 1999a). Subsequent investigations suggested that the eclipsing binary has a fainter visual companion at an angular distance of $\sim 12''$, with common proper motion (Giclas et al. 1959) and radial velocity (Delfosse et al. 1999b). This fainter companion is also a double system.

Complete light curves in R and I bands were published by Ribas (2003) who determined absolute parameters of CU Cnc by combining the photometric elements with the existing spectroscopic solutions. The derived orbital inclination was $i = 86.^\circ 34(\pm 0.03)$ indicating that it is a total eclipsing binary and absolute parameters can be determined in high precisions. Their results were: $M_1 = 0.4333(\pm 0.0017) M_\odot$, $M_2 = 0.3980(\pm 0.0014) M_\odot$, $R_1 = 0.4317(\pm 0.0052) R_\odot$, and $R_2 = 0.3908(\pm 0.0094) R_\odot$. It was found that the two components in the binary are fainter than other stars of the same mass with a magnitude difference about 1.4 mag in V and 0.35 mag in K band. As discovered in other eclipsing binary stars, most theoretically evolutionary models underestimate the radii of the component stars by as much as 10%.

High resolution spectra were obtained by Ribas (2003) that revealed very strong H_α and H_β emission features (double lines). As that of YY Gem, the H_α equivalent width of CU Cnc is rather large but not unreasonable when compared with young red dwarfs (e.g., Soderblom et al. 1991). However, the strong H_α emission in the two binary systems is more related to the tidally spin-up caused by orbital synchronization rather than age (e.g., Ribas 2003). Apart from showing H_α chromospheric emission, CU Cnc also displays strong of EUV and X-ray emission (e.g., Voges et al. 1999; Schmitt et al. 1995). The calculation of L_X/L_{Bol} by Ribas (2003) yielded a value of 10^{-3} that is very close to the value of YY Gem. As for the dark-spot activity of CU Cnc, the analysis of the light curve by Ribas (2003) indicated that there are two spots – one on each component. The spot on the primary component appears

to be relatively small (with a radius of 9° and 450 K cooler than the photosphere), while the secondary component has a much larger spot (with a radius of 31° and a temperature difference with the surrounding photosphere of 200 K).

Flares are known as sudden and violent events that release magnetic energy and hot plasma from the stellar atmospheres. They are observed on magnetically active stars and, much more closely, on the Sun. Observations have shown that flares in M-type stars occur more frequently than those on G- and K-type stars (e.g., Moffett 1974; Lacy et al. 1976; Henry & Newsom 1996). However, no flare activities on CU Cnc were observed. Here, we report the flares of CU Cnc observed in R band including a flare with the largest amplitude and showing quasi-periodic oscillations.

2. Optical flares from CU Cnc

To understand the properties of the variations of the light curves and the orbital period changes of red-dwarf eclipsing binaries (e.g., YY Gem, TU Boo, CU Cnc, FS Aur, NSVS02502726, and DV Psc), we were monitoring them photometrically by using two Andor DW436 2K CCD cameras amounted on the 1.0-m and 60-cm telescopes in Yunnan observatory. During the monitoring of CU Cnc with the 60-cm telescope on October 28, 2009, we were lucky to detect a large flare in the R-band (see in Fig. 1). The integration time for each CCD image was 90 s. Coordinates of the comparison and the check stars were $\alpha_{2000} = 08^h31^m37.4^s$ and $\delta_{2000} = +19^\circ23'49.5''$ for the comparison, and $\alpha_{2000} = 08^h32^m09.7^s$ and $\delta_{2000} = +19^\circ26'59.3''$ for the check star. The observed images were reduced by using PHOT (measure magnitudes for a list of stars) of the aperture photometry package of IRAF.

As shown in Fig. 1, the amplitude of the flare is about 0.52 mag and the duration time is about 73 minutes. Its characteristic shape shows a rapid brightness increase (the impulsive phase) followed by a gradual decline, which are similar to those seen in solar flares. This flare was occurring during the primary eclipse (from phase 0.9935 to phase 1) indicating that it is most probably from the secondary component. Meantime, due to high time resolution of our data, three small eruptions were observed to be superimposed on the flare, which are more clearly seen in the lower panel of Fig. 1. The duration time of each eruption is about 3 minutes and the mean amplitude is about 0.046 magnitudes. These properties indicate that there are quasi-period pulsations in the flare, which were often observed in solar flares with periods ranging from fraction of seconds to several minutes (e.g., Nakariakov & Melnikov 2009). The mean amplitude of the quasi-period pulsations is about 4.6 times larger than the photometric error (about $0.^m01$) suggesting that it is not from random noise in the light curve. After this flare, four smaller eruptions were observed subsequently indicating that

there are post-flare quasi-period pulsations, which were also observed in subsequent solar flares (e.g., Grechnev et al., 2003). The maximum relative luminosity at the flare peak can be calculated by using,

$$L_{Max} = 2.5^{-\Delta m_A} \times L_0, \quad (1)$$

where L_0 is the quiescent luminosity of the binary and Δm_A is the amplitude of the flare. It is shown that at the peak of the flare the luminosity of the binary increases by 1.61 times. By considering that both component stars in CU Cnc are similar, the luminosity of the flaring component should increase by about 3.22 times.

Three more flares in R band were found by following up monitoring with the 60-cm telescope. We used the following criteria. (a) A flare should last for several minutes and contain more than one data point, since a peak represented by a single data point could be due to cosmic rays from the direction of the stars, and (b) the amplitude of the peak should be no less than 0.03^m (three times of the photometric error about $0.^m01$). The one observed on December 10, 2009 occurred just after the secondary eclipse (as shown in Fig. 2), and the other two took place out of eclipses. We do not know the three R-band flares are from the more massive component or the less massive one. All of the three flares are shown in Fig. 2 where phases of the observation were computed based on the ephemeris given by Ribas (2003).

In all, we were monitoring CU Cnc for 90.8 hours. Meanwhile, R filter was used for 79.9 hours revealing a R-band flare rate of 0.05 flares per hour. The log of the photometric monitor of CU Cnc is listed in Table 1. The flare rate of CU Cnc is comparable with that of the other cool eclipsing binary star CM Dra (e.g., Kim et al. 1997). However, since the four flares were observed in R band indicating that they are energetic ones. We suspect that the true flare rate might be higher than this value because some less energetic flares can not be found in R band.

3. Discussions and conclusions

Since flares are most readily observed in U and B bands, the fact that the four flares were observed in R-band suggests that they are highly energetic. Among all of the R-band flares observed so far (see Table 2), the one from CU Cnc that took place on October 28, 2009 has the largest amplitude indicating that it is one of the most energetic giant flares. The detection of four R-band flares especially the very energetic one from CU Cnc reveals that it is a strong magnetically active system.

Quasi-periodic pulsations are a common feature of the flare energy release process of

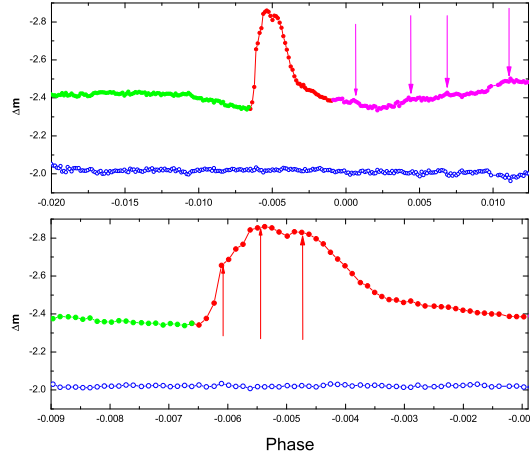


Fig. 1.— A very energetic R-band flare from CU Cnc. All of the solid dots in different colours represent the magnitude difference between CU Cancrri and the comparison star. The energetic flare (red dots) was observed on October 28, 2009 and occurred during the primary eclipse indicating that it may be from the secondary component. Green solid dots refer to the brightness in "quiescent" state, while blue open circles represent the difference between the comparison and the check stars. Magenta arrows in the upper panel show the times of the four smaller post-flare eruptions. Details of the properties of the flare are displayed in the lower panel where three small eruptions (the arrows) are detected during the flare suggesting there is a quasi-periodic oscillation in the flare. Phases of the observation were calculated with the linear ephemeris given by Ribas (2003): $T(\text{Min.}I) = HJD\ 2450208.5068 + 2.771468 \times E$.

Table 1: The log of the photometric monitor for CU Cnc.

Date	Start UT	End UT	Filter	Flare	Telescopes
8 December 2007	19:00:31	19:58:03	R	No	The 1.0-m
28 March 2008	14:56:31	17:39:51	I	No	The 1.0-m
28 October 2009	20:04:29	22:34:18	R	Yes	The 60-cm
22 November 2009	18:35:59	20:29:45	R	No	The 60-cm
28 November 2009	16:57:26	22:14:32	V	No	The 1.0-m
29 November 2009	16:36:07	19:18:42	R	No	The 60-cm
30 November 2009	17:13:44	18:15:13	R	No	The 60-cm
1 December 2009	16:24:45	22:31:08	R	No	The 60-cm
3 December 2009	16:50:52	22:02:32	V	No	The 1.0-m
7 December 2009	16:13:10	20:29:47	R	No	The 60-cm
8 December 2009	15:58:09	22:50:54	R	Yes	The 60-cm
9 December 2009	16:10:47	22:59:43	R	No	The 60-cm
10 December 2009	16:08:36	22:53:47	R	Yes	The 60-cm
11 December 2009	17:09:30	22:48:37	R	No	The 60-cm
12 December 2009	15:46:17	23:03:46	R	No	The 60-cm
13 December 2009	16:16:59	20:18:19	R	Yes	The 60-cm
14 December 2009	15:40:24	21:53:20	R	No	The 60-cm
15 December 2009	15:38:29	23:02:50	R	No	The 60-cm
16 December 2009	15:38:04	20:09:29	R	No	The 60-cm
17 December 2009	15:38:09	20:40:32	R	No	The 60-cm

Table 2: Flares of cool stars observed in R-band.

Star names	Flare amplitude Δm	Total duration Minutes	Ref.
V405 And	0.12	80	Vida et al. (2009)
CU Cnc	0.52	73	The present authors
CU Cnc	0.10	17	The present authors
CU Cnc	0.05	23	The present authors
CU Cnc	0.04	38	The present authors
FR Cnc	0.21	41	Golovin et al. (2007)
WY Cnc	0.045	64	Kozhevnikova et al. (2006)
CM Dra	0.23	60	Nelson & Caton (2007)
CM Dra	0.04	135	Nelson & Caton (2007)
CM Dra	0.08	135	Nelson & Caton (2007)
CM Dra	0.09	135	Nelson & Caton (2007)
CM Dra	0.02	34	Nelson & Caton (2007)
CM Dra	0.02	40	Nelson & Caton (2007)
CM Dra	0.21	92	Kozhevnikova et al. (2004)
CM Dra	0.10	70	Kozhevnikova et al. (2004)
CM Dra	0.03	21	Kozhevnikova et al. (2004)
CM Dra	0.21	34	Kozhevnikova et al. (2004)
DV PSc	0.02	13.5	Zhang et al. (2010)
XY UMa	0.04	30	Zeilik et al. (1982)

the Sun that can be seen in all observational bands with periods from a fraction of a second to several minutes (e.g., Nakariakov & Melnikov 2009). As for the stellar flares, a few cases of quasi-periodic oscillations were reported. Rodonò (1974) detected white light intensity oscillations (13s) during a flare on the red-dwarf star II Tau. Mathioudakis et al. (2003) observed 5 minutes white light intensity oscillations in a flare on the RS CVn-type eclipsing binary II Peg. During of the observation, quasi-period pulsations with a mean period of 3 minutes were discovered on the largest-amplitude flare. Observational evidence revealed that there exist post-flare oscillations. It is the first time to detect quasi-periodic oscillations during and after the flaring energy release of an close eclipsing binary star, and the physical mechanisms to cause it are unclear.

At least 80% of all stars in the Galaxy are Red dwarfs. However, physical properties of these most common stars are poorly understood. The serious problem in this field is the significant discrepancy between the theoretical and observational mass-radius relations, i.e., the observed radius is about 10% larger than that computed from theoretical models (e.g., Blake et al. 2008; Irwin et al. 2009; Torres & Ribas 2002; Morales et al. 2009). Some authors have realized that this discrepancy could attribute to the strong magnetic activities of the components in short-period red-dwarf eclipsing binaries (e.g., Mullan & Macdonald 2001; Chabrier et al. 2007; López-Morales 2007; Torres et al. 2010; Morales et al. 2008, 2010; Devor et al. 2008). Mullan & Macdonald (2001) investigated the effects of magnetic field on stellar structure and pointed out that their magnetic models predicted active M-type dwarfs tend to have larger radii.

To resolve the mass-radius discrepancy, two scenarios were considered (e.g., Chabrier et al. 2007). One is that magnetic field and rotation can induce reduction of the efficiency of large-scale thermal convection in the interior and thus can lead to less efficient heat transport. The other is that the magnetic dark-spot coverage decreases the star’s radiating surface and also yields a smaller effective temperature and a larger radius. Either one or a combination of the two can predict larger radius than standard stellar models, but the effect of dark spots is significant over the entire low-mass domain (e.g., Chabrier et al. 2007; Morales et al. 2010). However, it is shown that high spot coverage (up to 50-100%) is needed to be assumed to solve the significant discrepancy (Morales et al. 2010). On the observational aspect, to explain the observations of M-dwarfs in the young open cluster NGC 2516, the required spot coverage is about 50 per cent in rapidly rotating M-type dwarfs (e.g., Jackson et al., 2009). Reiners et al. (2009) claimed very high filling factors of magnetic field in rapidly rotating M-dwarfs.

In the mass-absolute magnitude diagram, CU Cnc was found to be fainter than other stars of the same mass with a magnitude difference about 1.4 mag in V band. The apparent

faintness was explained by Ribas (2003) as: (i) its components are some 10% cooler than similar-mass stars or (ii) there is some source of circumstellar dust absorption. The detection of the four R-band giant flares together with other strong chromospheric and coronal emissions (see in Section 1) support the conclusion that the faintness of the stars in CU Cnc is caused by groups of dark spots via the enhanced magnetic activity of the cool components. The total luminosity of a spotted star is given as (e.g., Chabrier et al. 2007; Morales et al. 2010),

$$L = S[(1 - \beta)\sigma T^4 + \beta\sigma T_s^4], \quad (2)$$

where σ is Stefan-Boltzmann constant, T_s the temperature of the spotted area, T the temperature of the immaculate surface, and $\beta = \frac{S_s}{S}$ is the fraction of stellar surface covered by dark spots, where S_s is the spotted area and S is total area of the active star. As pointed out by Ribas (2003), no empirical information is available on the temperature of the spots. Photometric solutions of CU Cnc derived by Ribas (2003) indicate that the spot on the primary of CU Cnc is 450 K cooler than the photosphere, while the one on the secondary has a temperature difference with the surrounding photosphere of ~ 200 K. During the modulating of the light curves of M-type eclipsing binaries, Morales et al. (2010) assumed the temperature of spots is about ~ 500 K cooler than the photosphere. Here, by assuming $\frac{T_s}{T} = 0.85$, the faintness of CU Cnc can be explained by 93% of dark-spot coverage on the photospheric surfaces (by considering the 'mean' component). If we take into account that the radius changes as the star becomes spotted, the coverage of the dark spots should be larger. Observations of CU Cnc may provide observational evidence for highly dark-spot coverage on component stars in short-period M-type eclipsing binary stars, and thus the mass-radius problem can be resolved.

However, by modeling the light curve of CU Cnc, Ribas (2003) obtained a significantly lower spot coverage than our results. This may be caused by the fact that the coverage of dark spots for red-dwarf eclipsing binaries may be underestimated during the photometric solution because photometric changes of eclipsing binaries applied to determine the spot parameters are only sensitive to the contrast between areas with different effective temperatures and not to the total surface covered by spots (Morales et al. 2010). On the other hand, perhaps axial symmetry of the spots also plays a role. Both components in CU Cnc are at the upper boundary of full convection. M-type dwarfs near the boundary like the two in CU Cnc exhibit large-scale magnetic fields which are very strong axisymmetric poloidal and nearly dipolar with very little temporal variations (Morin et al. 2010). It is possible that the stable and enhanced large-scale magnetic fields associate with the extremely high dark-spot coverage discovered in CU Cnc.

As shown in Fig. 2, the out-of-eclipse brightness of CU Cnc is changed by 0.035 magnitude from Dec. 8 to 13, 2009. This is evidence for dark-spot activity revealing a change of dark-

spot coverage about 6.7%. Because of the tidal locking and the effect of the close companions, the magnetic activity levels of close binaries are much higher than those of single stars with the same mass. Strong magnetic activity may significantly affect the structure and evolution of eclipsing binaries and the physical properties of these objects depart from the single ones (e.g., Mullan & Macdonald 2001; Chabrier et al. 2007).

To check whether similar faintness were observed in other M-type eclipsing binary stars or not, we have compared parameters of some eclipsing binaries (Kraus et al. 2011; Irwin et al. 2009, 2011; Blake et al. 2008; Morales et al. 2009; Vaccaro et al. 2007; López-Morales & Ribas 2005; López-Morales et al. 2006; Torres et al. 2002; Ribas et al. 2003; Hebb et al. 2006; Dimitrov & Kjurkchieva 2010; Moceroni et al. 2004; Creevey et al. 2005; Devor et al. 2008). The mass-luminosity relation is shown in Fig. 3. For comparison, parameters of some single stars given by Xia et al. (2008) and Preibisch & Mamajek (2008) are also shown in the figure where solid dots refer to the eclipsing binaries, while open circles represent single stars. Also display in this figure as solid stars are the positions of the components in CU Cnc. The masses of those single stars were estimated with their colors (or spectral types) and magnitudes by considering their evolutionary tracks (e.g., Baraffe et al. 1998). As displayed in Fig. 3, even those single stars are still young and magnetically active, they are usually brighter than the components of short-period eclipsing binaries with the same mass indicating highly dark-spot coverage on the component stars. However, since the masses have been measured/estimated in completely different ways, the final conclusion that eclipsing binaries are fainter at the same mass would be premature. Moreover, the photometric solutions of the eclipsing binaries were obtained with several different software packages (e.g., Wilson & Devinney 1971; Popper & Etzel 1981; Southworth et al. 2004; Prsa & Zwitter 2005). Further brightness comparison between M-type components in eclipsing binaries and single red dwarfs and uniform solutions of eclipsing binaries with the same method are required in the future.

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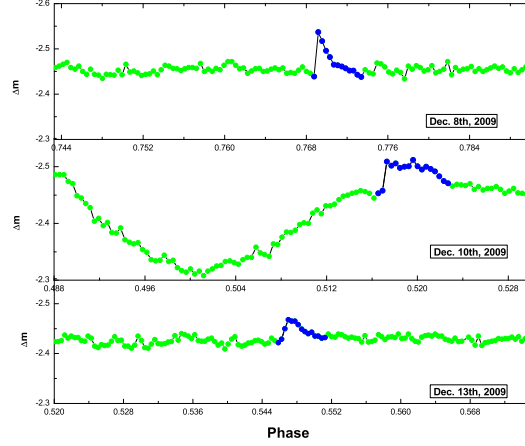


Fig. 2.— Three R-band flares of CU Cnc observed on December 8, 10, and 13, 2009. Phases of the observation were calculated by using the linear ephemeris given by Ribas (2003).

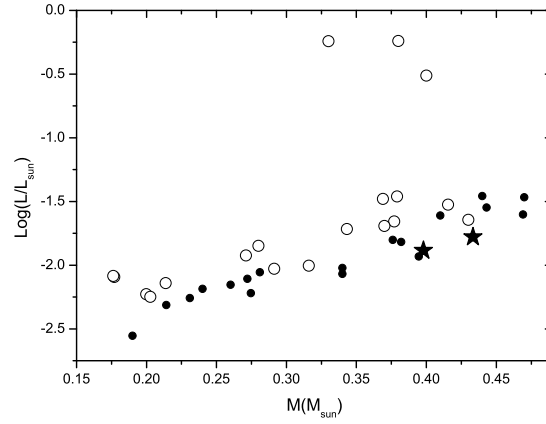


Fig. 3.— Mass-luminosity relation for M-type stars with similar to the components in CU Cnc. Solid dots represent to the eclipsing binaries, while open circles refer to single stars. The positions of the components in CU Cnc are shown as solid stars.

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